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Vane Design for the Coastal Ocean Lagrangian (COOL) Float

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Technical Report
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Acknowledgments

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Introduction

The COastal Ocean Lagrangian (COOL) float is being designed as a three dimensional Lagrangian follower of water parcels. It will incorporate the features of the f/h float (Rossby et al, 1994) and an isobaric vertical current meter (Voorhis, 1968) that we will refer to as the VCM. The f/h floats are isopycnal floats capable of changing their volume at preprogrammed times. The technology for this float is already available at the Graduate School of Oceanography. The VCMs are isobaric floats equipped with vanes. Water flowing vertically past these vanes rotates the float and based on this rotation rate, the vertical velocity of water can be calculated. Due to the isobaric nature of these floats, they mainly measure the vertical velocity of internal waves. The COOL float, however, being isopycnal, would bob up and down with the internal waves. The vertical velocity measured from such an isopycnal platform would therefore be the diapycnal velocity. By using the measured diapycnal vertical velocity, the COOL float would be programmed to change its density and keep up with the water parcel that it is tracking. Therefore to make the COOL float truly Lagrangian, accurate measurement of the vertical (diapycnal) velocity is important.

Although isobaric VCMs have been previously developed and deployed (Voorhis 1968; Webb and Worthington, 1968), not much is known about how vane geometry affects the float's response to vertical velocities. In these deployments of VCMs the choice of number and orientation of the vanes seemed arbitary. Here we determined the sensitivity of the float's rotation rate to vertical velocity past it to the geometry of the vanes. We tested the float's response to the size, number and area of vanes, and the distance the vanes were located from the body of the float.

Experimental Design

To avoid the difficulties of handling an actual COOL float, which would be made of glass and would have a compressee (which makes the float's total compressibility equivalent to seawater) and ballast weights attached to it, we used a substitute — the "prototype" — during these experiments. We used a 2.1-m-long PVC tube with an outer diameter of 0.098 m as a surrogate for the COOL float, whose dimensions would be 2.2 m and 0.095 m respectively. Our prototype float is shown in Figure 1. A difference between our prototype and the final float is in the shape of the top and bottom ends. The prototype is sealed at both ends with blunt O-ring end caps. Not only do the two ends of the COOL float differ from this, they differ from each other as well: while its top is rounded, its bottom is blunt, with ballast weights suspended from it. However, since the total area that the vanes present to the flow is much greater than the area of the ends, this difference may not significantly affect the drag.

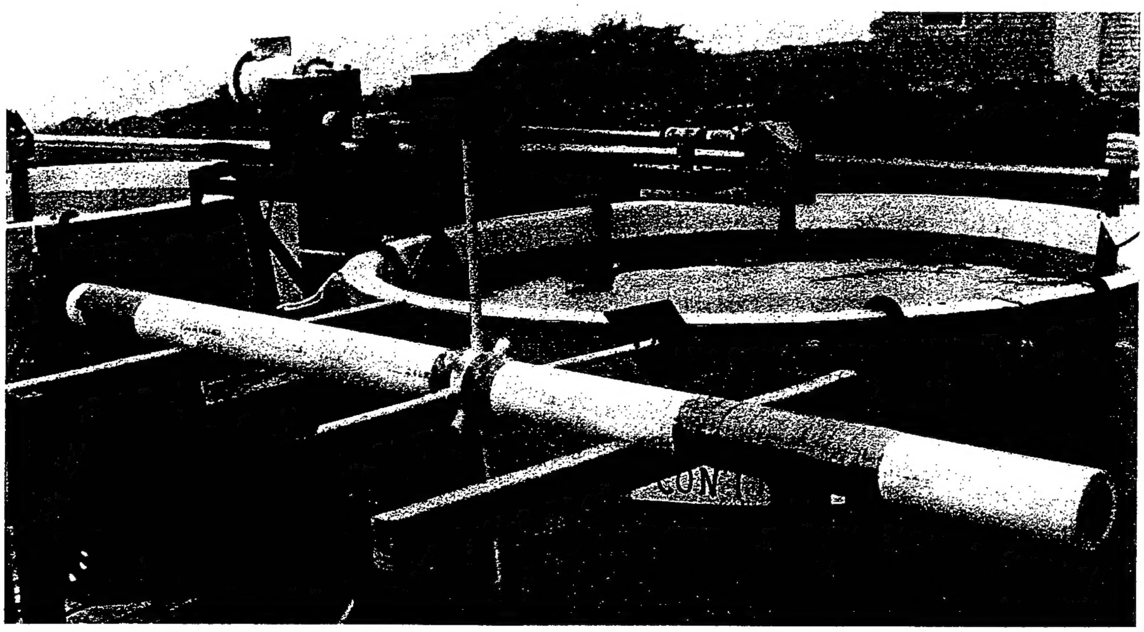


Figure 1: *The prototype float beside the Marine Ecosystems Research Laboratory (MERL) tank in which it was tested. As shown, it has four 6 $''$ × 6 $''$ vanes (paddles) attached to 12 $''$ arms.*

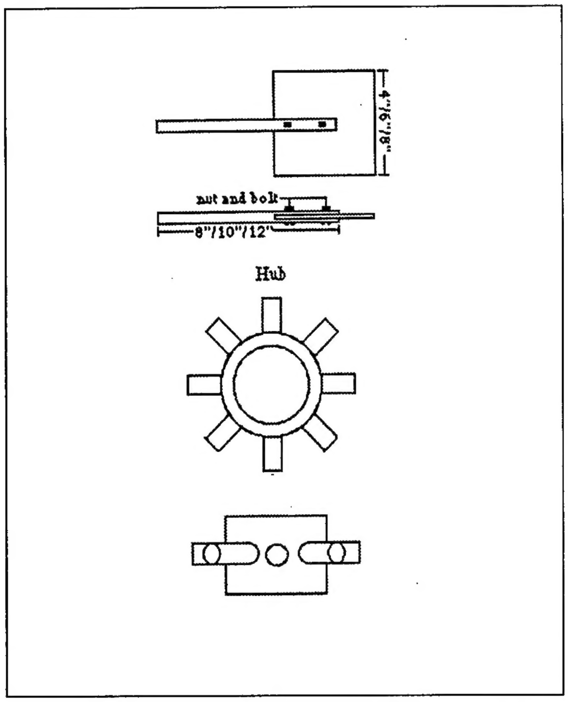


Figure 2: *Plan and side view of the vane assembly. The vane is made up of a square plastic paddle screwed onto a PVC arm. The vanes are then press-fitted into the hub, which is taped onto the body of the float (see Figure 1).*

The vanes on the PVC float will rotate it when water flows vertically past it. The vanes were made up of paddles — square plastic plates — attached to the end of PVC arms. The vanes were press-fitted into a hub that was taped onto the float (Figure 2). The Precision Navigation Vector 2X Compass Module inside the float (Figure 3) measured magnetic field and supplied a heading for the float using two perpendicular solenoids.

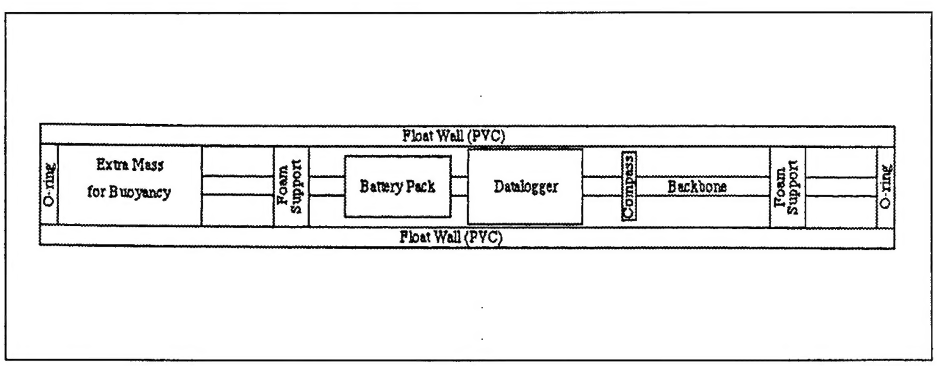


Figure 3: *Schematic representation of the inside of the prototype. The heavy battery pack and the ballast weights at the bottom made the prototype almost neutrally buoyant and kept the float vertical.*

The Onset Computer Tattletale Model 6F data logger recorded the compass heading every second. Once the experiment was completed and the float was out of water, these headings were downloaded and the rotation rate of the float determined. In addition to these two instruments and the battery pack that powered them, ballast weights were placed inside the float to make it almost neutrally buoyant.

There are two ways to test how the float would respond to vertical motion: either dragging it vertically through still water or holding its location fixed and allowing water to flow past it. For this study we chose the first of these methods. In one of the Marine Ecosystems Research Laboratory (MERL) tanks at GSO, the PVC prototype float was raised and lowered by wrapping a monofilament line around the drive shaft of a variable speed motor (Figure 4). To reduce any torque in the monofilament due to twisting by the float's rotation and the resulting effect on the rotation of the float, we used several swivels in series. The float was raised and lowered in the tank at various vertical speeds. These vertical speeds were measured by timing the passage of marked-length segments of the monofilament. To ensure a constant vertical velocity for a given speed of the motor, the line was wound on the shaft as close to a circle as possible. In spite of this precaution, changes in the vertical velocity were occasionally observed for a given speed setting of the motor — the actual reason for this variation is unknown.

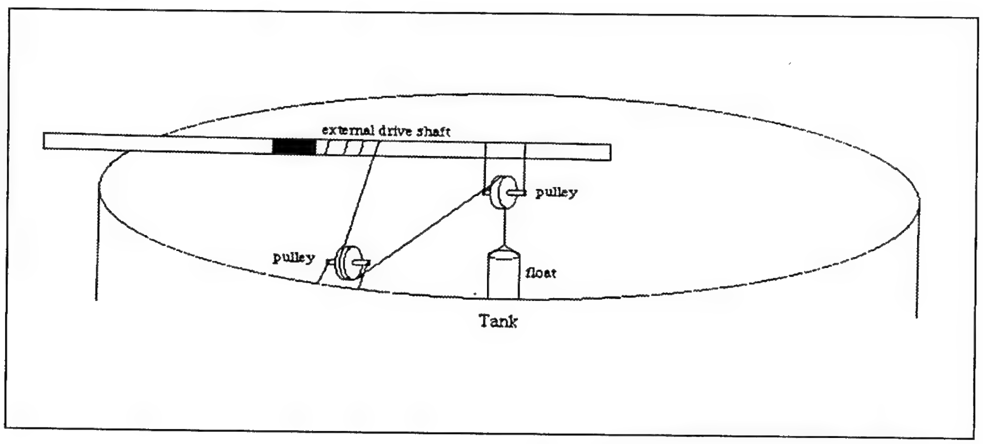


Figure 4: *The prototype was raised and lowered in one of the MERL tanks at GSO. Monofilament line wound on the motor shaft was passed through two pulleys and attached to the float through swivels.*

A series of experiments were performed for different sizes, orientations and numbers of the paddles, and different lengths of the arm connecting the paddle to the hub. One parameter was varied at a time (Table 1). However, all possible combinations were not examined.

Data Analysis

In our analysis of the data, the vertical velocity of the float was taken as the mean velocity for a given raising or lowering speed even though it varied by as much as 10% in some cases. The angular velocity (ω) of the float was obtained from average rate of change in the compass heading. Owing to torque in the monofilament line due to a twisting of the line and/or a vertical velocity or vorticity in the tank, there was an ambient rotation of the float on which the angular velocity due to vertical motion was superimposed. In Figure 5 the ambient rotation can be seen as the drift of the baseline. Before analyzing the data, we first removed the ambient rotation by using the best-fit line as shown in Figure 5. (Since the ambient rotation rate need not be constant, a linear fit may not remove all the effects of this ambient rotation.) During a given raising or lowering event, changes in vertical velocity caused the angular velocity to vary. Although the angular velocity changed, the variation in ω about the mean for the entire event remained small. As an example, consider the case where the vertical velocity varied the most (Figure 6). We found the mean slope (angular velocity) to be -0.7896 deg s^{-1} and the standard deviation to be 0.0039 deg s^{-1}, using the bootstrap method. It should be noted that this small standard deviation is that of the mean slope and not of the instantaneous slope. Once the angular velocity (ω) for each event was determined, we determined its dependence on the vertical velocity (w). For each vane geometry, we determined the mean slope of ω versus w and standard deviation of this slope, using the bootstrap method. The slope of the curve of ω versus w is indicative of the "sensitivity" of the vane geometry to vertical velocities. The greater the slope, the greater the resolution in determining w from ω. For the remainder of this report, we will not show the original data (i.e., heading versus time) but only the mean vertical velocities (w) and the mean angular velocities (ω) for the various configurations of the vanes.

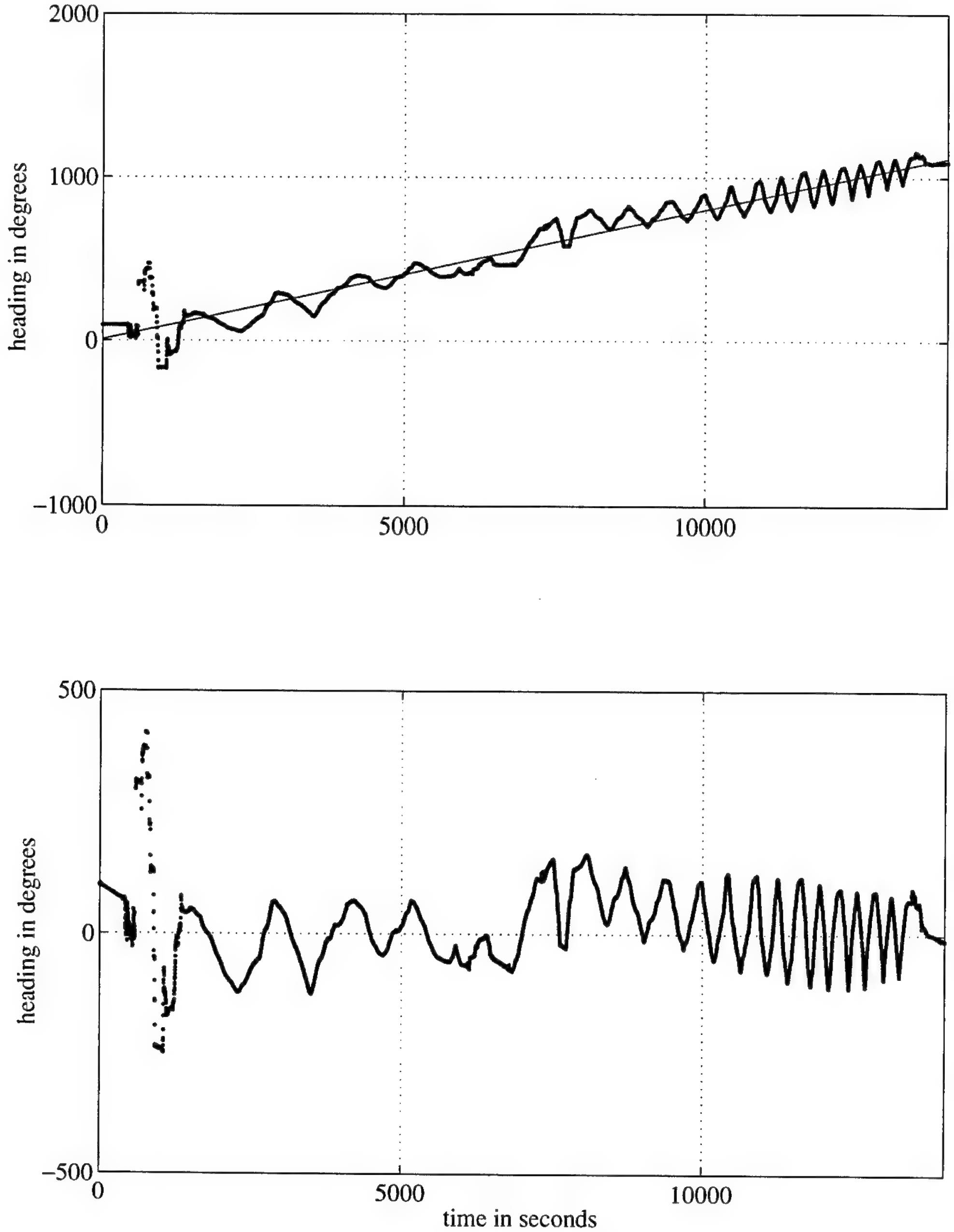


Figure 5: *The upper panel shows the compass heading versus time. In spite of the swivels, torque in the monofilament line and ambient circulation in the tank caused a rotation of the float, which was superimposed on the rotation due to the vertical velocity past the float. This mean rotation (thin line) was removed before the data was analyzed (lower panel). The magnitude of the mean rotation for this case is 0.08 deg* s^{-1}*. On another occasion, this rotation rate reached 0.3 deg* s^{-1}*. However, this rotation rate is no larger than some of the lowest measured rotation rates for the smallest vertical velocities.*

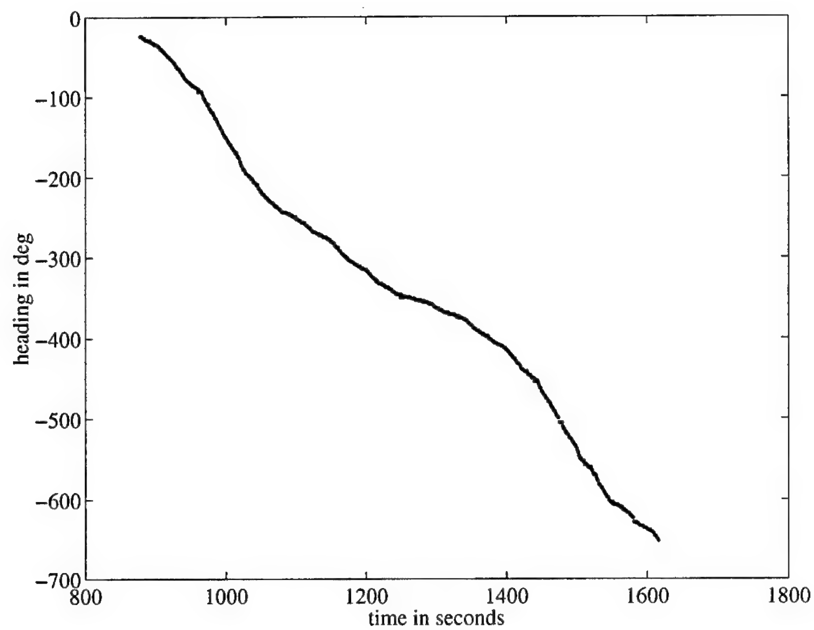


Figure 6: *Variations in the vertical velocity of the float while being raised or lowered caused its angular velocity to also vary. Even in the worst of such cases – shown above – the standard deviation of the mean slope calculated using the bootstrap method, -0.7896 deg* s^{-1}*, was only 0.0039 deg* s^{-1}.

Results and Discussion

Of principal interest in this study is how the vane geometry affects the ratio of angular velocity to vertical velocity past the float — i.e., the sensitivity of the float's response to vertical velocity. The parameters of the vane geometry that were varied (Table 1) were size, number and orientation of vanes, and the distance of the vanes from the float body (i.e., arm length). The effect of each of these parameters was studied by varying one parameter at a time while holding all others constant. We present the results in two kinds of plots: (1) Angular velocity ω versus vertical velocity w for each case, and (2) ω/w versus the parameter being varied (Figures 8–11). From the second of the these plots we should be able determine how sensitivity may be affected by a parameter. To facilitate comparison between all of the cases, the scale of angular velocity and vertical velocity axis in each of these plots is the same.

Parameters for which the prototype was tested			
Arm length in inches	Paddle size: length of each side	Number of paddles	Orientation of paddle to the horizon, in deg.
12	6	4	30
12	6	4	60
12	6	6	30
12	6	8	30
12	6	8	45
8	6	8	15
8	6	8	30
8	6	8	45
6	4	8	30
6	6	8	30
6	8	4	30
6	8	6	30
6	8	8	30

Table 1: *The sensitivity of the float was tested for each of the above combinations of parameters.*

Reducing the arm length increases the sensitivity, ω/w, of the float to vertical velocity (Figure 7). Orienting the paddles closer to the horizontal increases the rotation for a given vertical velocity (Figure 8). The dependence of sensitivity on the arm length is also evident

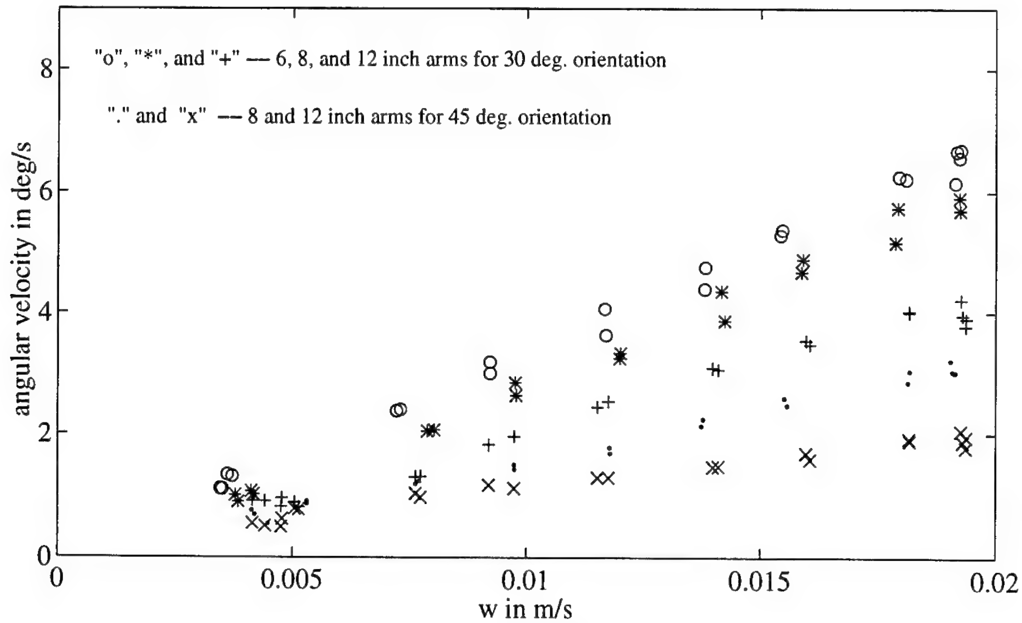
from this figure. Sensitivity does not change significantly with the number of paddles. In Figure 9 we see no significant difference between sensitivity for six and eight paddles while that for four paddles is lower, at the 95% confidence interval. However, in figure 10, the sensitivities for four, six and eight paddles are not significantly different, again at the 95% confidence interval. The sensitivity does not significantly vary with paddle size (Figure 11). Part of the difference between the sensitivities for different numbers or sizes of paddles could merely be an artifact of the subtraction of the liner "baseline", mentioned earlier. Over the range of vertical velocities at which the float was raised and lowered in water, we see a linear dependence of ω on w for all the cases (the upper panels of Fig 7–11). We expect this linear dependence to hold for even smaller values of w.

We can explain most of our observations based on two dimensional flow around the paddles. When the float is being dragged through water, the net force perpendicular to the face of the paddles must be zero (its rotation is like the motion of a screw being passed through a nut) and this can be caused only by a flow parallel to the face of the paddles — (1) the components of the form drag due to vertical and tangential velocities cancel out, and (2) no lift is produced because the flow is symmetric on both sides of the plate. Consider a paddle oriented at θ to the horizontal and at a radial distance L (Figure 12). A flow parallel to the face of the paddle implies that float is rotating at an angular velocity ω such that the ratio of vertical velocity (w) to tangential velocity ($\omega \times$ L) be equal to $\tan(\theta)$.

From the measured angular and vertical velocities, we can see that the flow over the paddles was nearly parallel to their faces. However, due to the variation of the tangential velocity along the leading edge of the paddle (as not all points on the leading edge are at the same radial distance) and due to the highly three-dimensional nature of the flow around the paddles (because the aspect ratio is unity), the water should not be expected to flow exactly parallel to the face of the paddle.

The prototype seemed to respond quickly to changes in vertical velocity. Consider the case where the float was lowered at 0.0040 ms^{-1} and then pulled up at the same vertical speed with the motor taking a few seconds to reverse the direction. The float responded almost instantaneously to this change (Figure 13). As the prototype and the COOL float have nearly the same mass and moment of inertia, we can expect the COOL float to respond to changes in vertical velocity on time scales of this order.

Torque from the twisting of the monofilament line that was not removed by the swivels impeded the rotation of the float. Also, ambient circulation in the tank may have caused the float to rotate. To determine whether this is a feasible explanation for the observed mean rotation of the float, let us consider the mean rotation mentioned earlier (Figure 5). While the mean rotation rate in this case was 0.08 deg s^{-1}, it was observed to be as high as 0.3 deg s^{-1} on another occasion. With a sensitivity ω/w of 320 deg/m (approximately the result



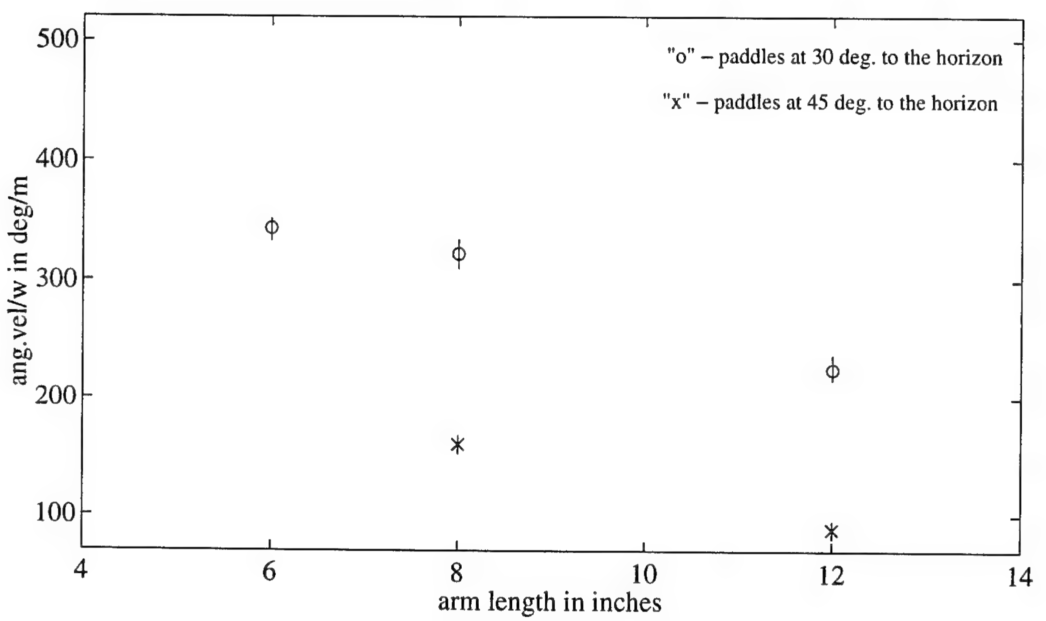
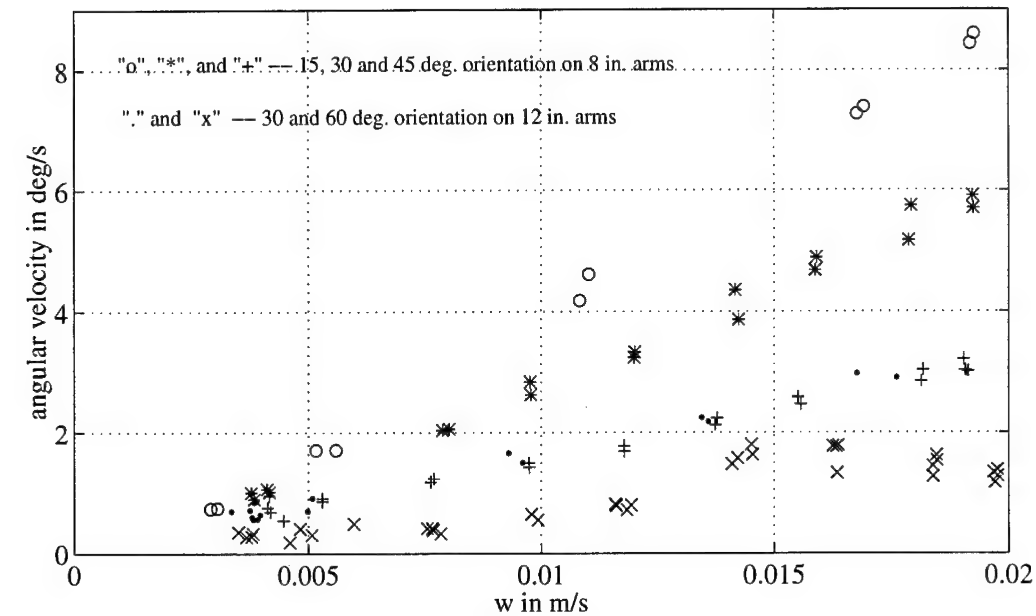


Figure 7: *Float rotation rate dependence on extent of vanes. One set of measurements involved 6 ″, 8 ″ and 12 ″ arms holding eight paddles of 6 ″ sides at 30 ° to the horizontal. In another set, 8 ″ and 12 ″ arms held eight 6 ″× 6 ″ paddles at 45 ° to the horizontal. The top panel shows ω against w for the five cases. The bottom panel shows the mean slope for each of the five curves of ω vs. w in the top panel. This slope is the "sensitivity", ω/w, of the float for a given set of parameters. The error bars in the bottom panel represent the 95% confidence interval of the slope.*



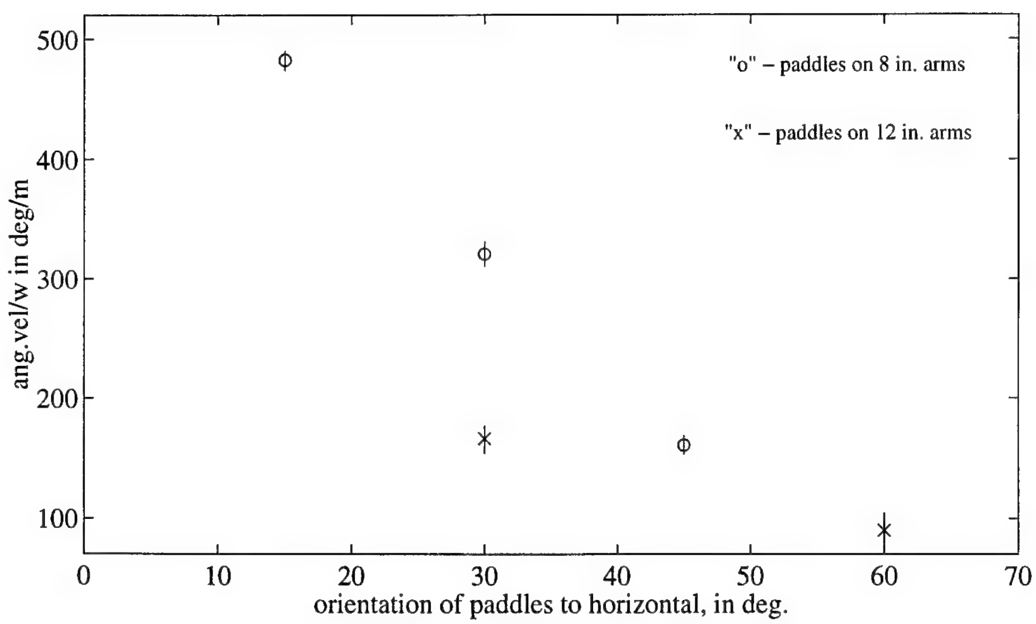


Figure 8: *Float rotation rate dependence on orientation of vanes. One set of measurements involved eight paddles of 6 " sides on 8 " arms oriented at 15 °, 30 °, and 45 ° to the horizontal. In another set, 12 " arms held four 6 "× 6 " paddles at 30 ° and 60 °. The top panel shows ω against w for the five cases. The bottom panel shows the mean slope for each of the five curves of ω vs. w in the top panel. This slope is the "sensitivity", ω/w, of the float for a given set of parameters. The error bars in the bottom panel represent the 95% confidence interval of the slope.*

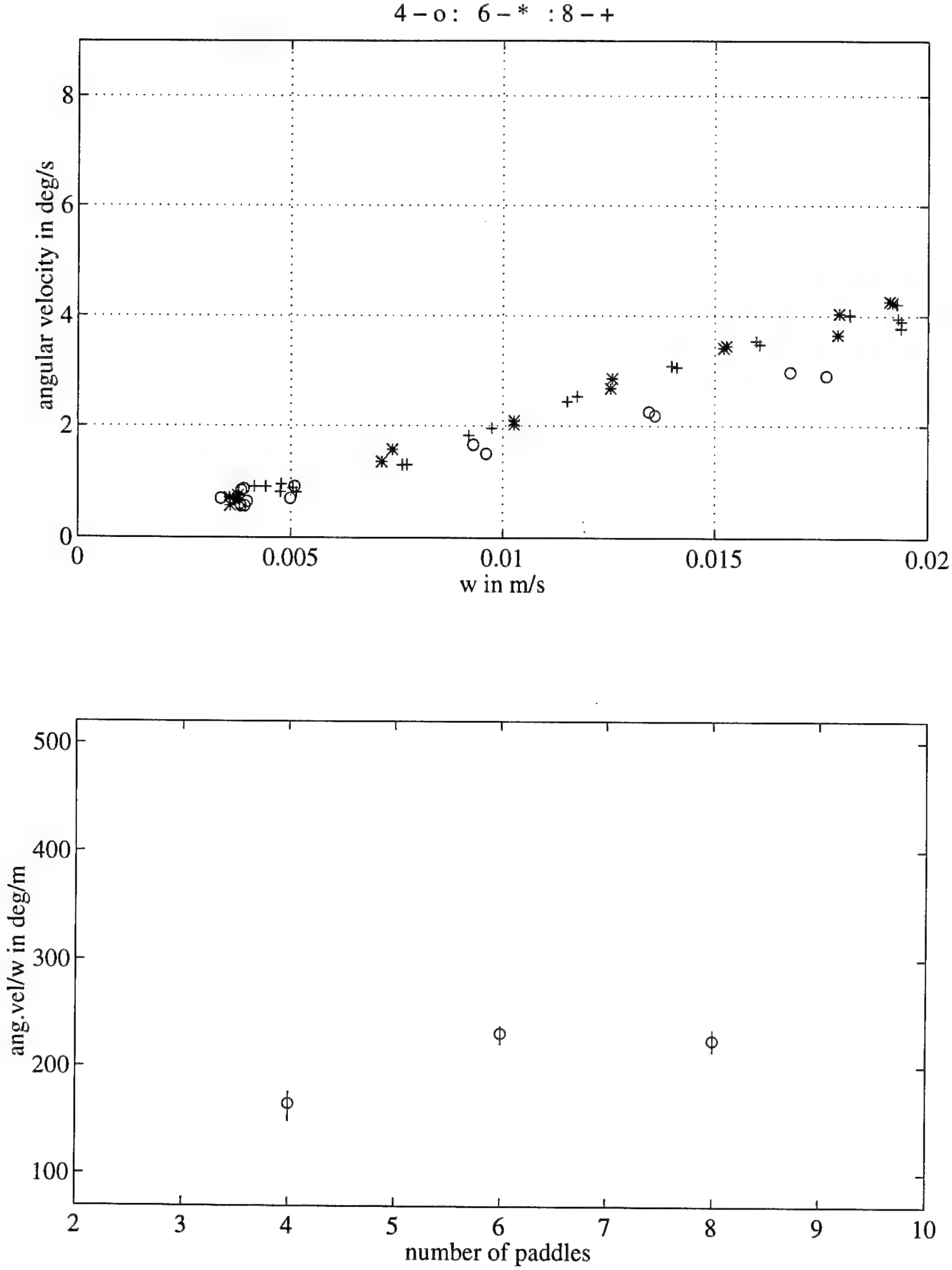


Figure 9: *Float rotation rate dependence on the number of vanes — four, six, and eight paddles of 6 " sides on 12 " arms oriented at 30 ° to the horizontal. The top panel shows* ω *against* w *for the three cases. The bottom panel shows the mean slope for each of the three curves of* ω *vs.* w *in the top panel. This slope is the "sensitivity",* ω/w*, of the float for a given set of parameters. The error bars in the bottom panel represent the 95% confidence interval of the slope.*

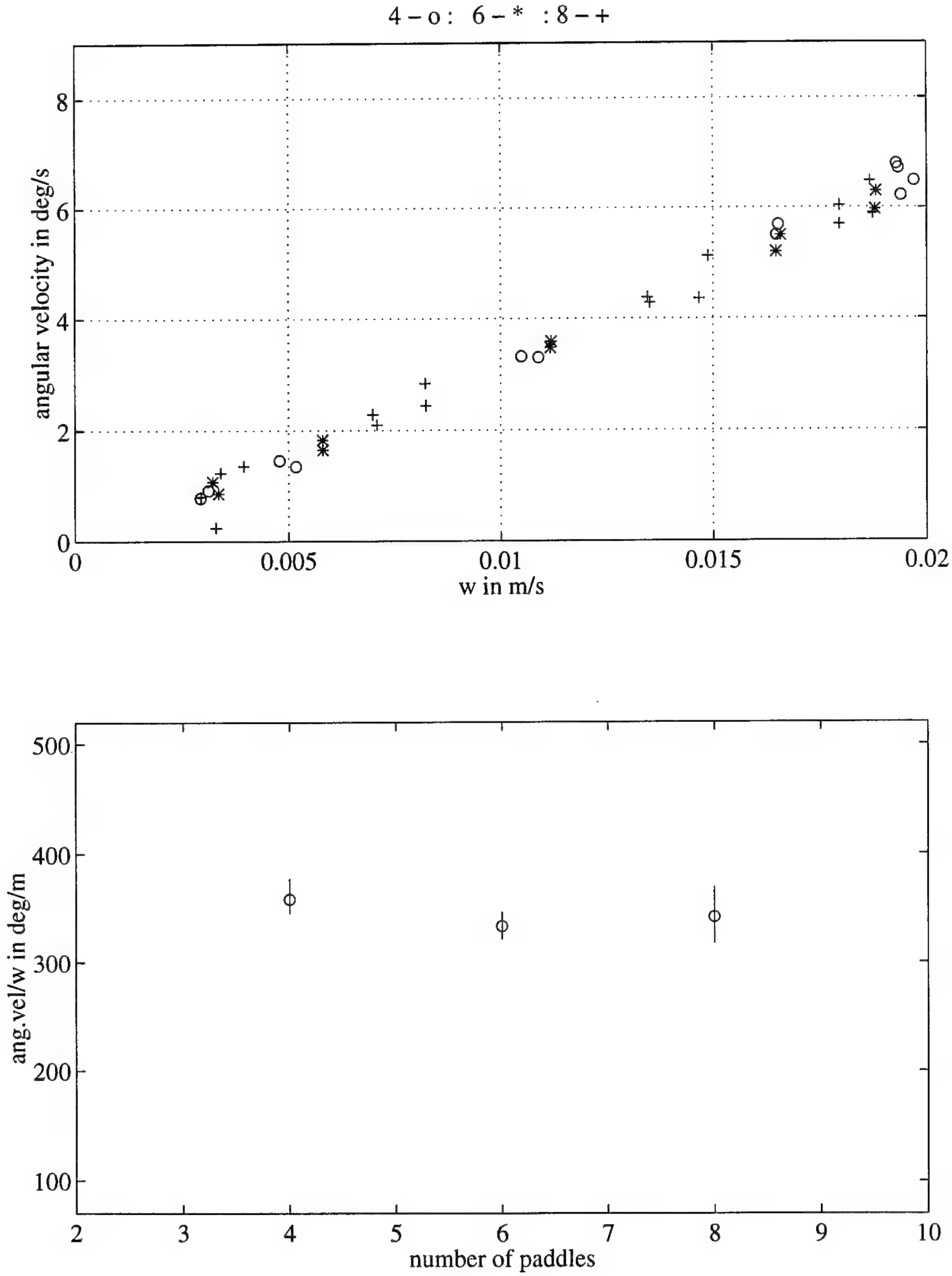


Figure 10: *Float rotation rate dependence on the number of vanes — four, six, and eight paddles of 8 ″ sides on 6 ″ arms oriented at 30 ° to the horizontal. The top panel shows ω against w for the three cases. The bottom panel shows the mean slope for each of the three curves of ω vs. w in the top panel. This slope is the "sensitivity", ω/w, of the float for a given set of parameters. The error bars in the bottom panel represent the 95% confidence interval of the slope.*

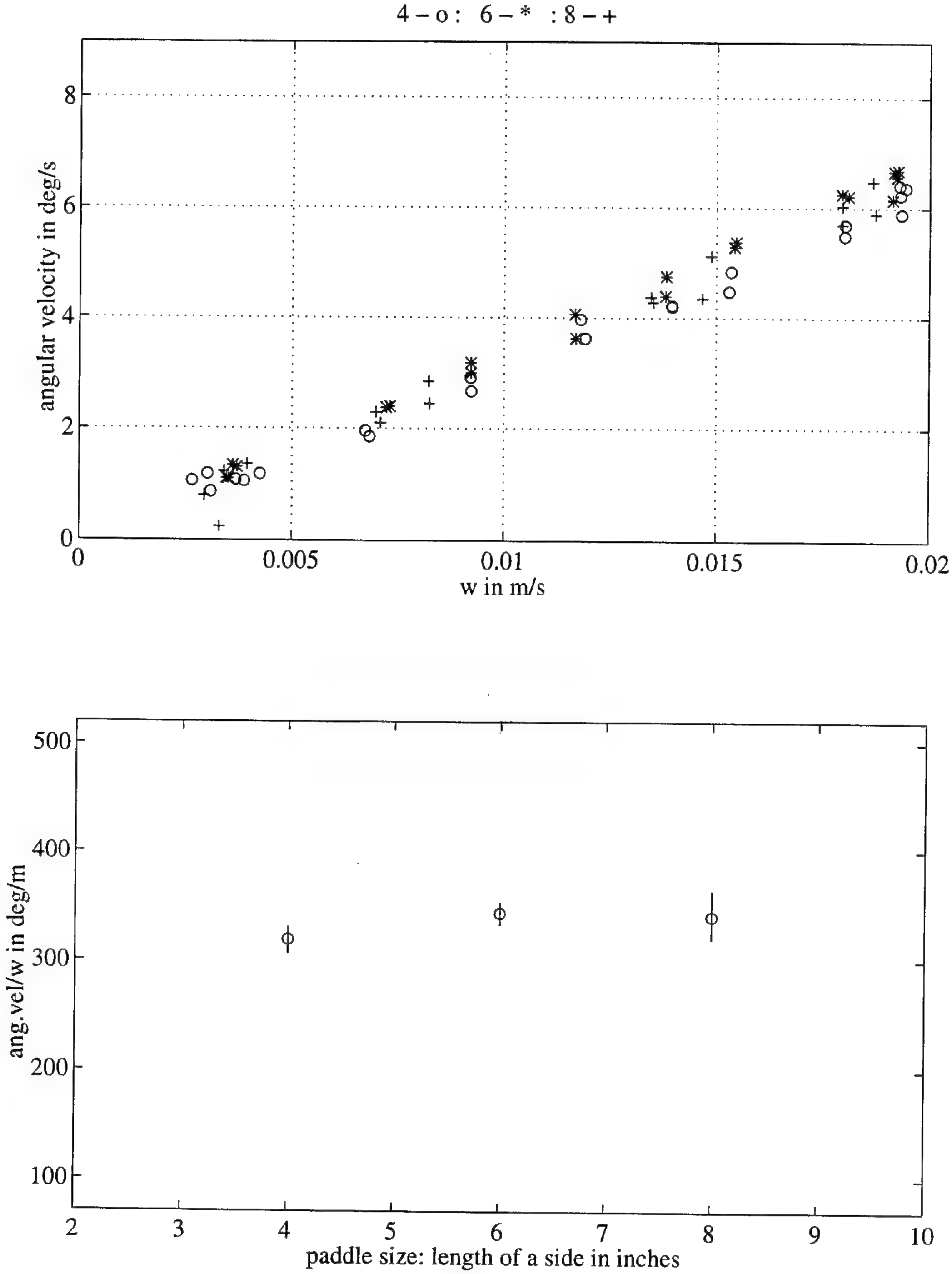


Figure 11: *Float rotation rate dependence on the size of vanes — eight paddles of 4 ", 6 ", and 8 " sides on 6 " arms oriented at 30 ° to the horizontal. The top panel shows ω against w for the three cases. The bottom panel shows the mean slope for each of the three curves of ω vs. w in the top panel. This slope is the "sensitivity", ω/w, of the float for a given set of parameters. The error bars in the bottom panel represent the 95% confidence interval of the slope.*

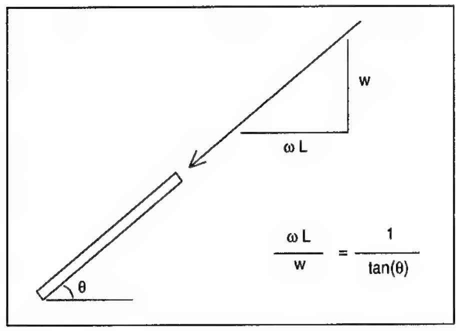


Figure 12: *Schematic of a paddle oriented at θ to the horizontal and at a radial distance of L from the float. For no net force perpendicular to the face of the paddle, the flow should be parallel to the face of the paddle. This can be accomplished by the paddle moving horizontally with velocity ωL such that* $\frac{vertical\ velocity}{tangential\ velocity} = tan(\theta)$.

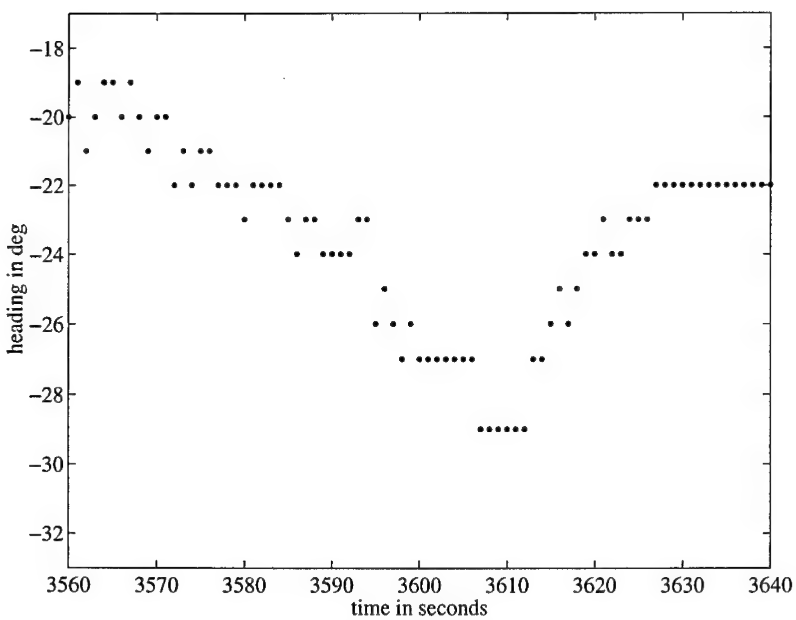


Figure 13: *Heading of the float with four paddles of 6 $''$ sides oriented at 45 ^{o} to the horizontal on 12 $''$ arms, for a period when w changed from -0.0040 ms^{-1} to +0.0040 ms^{-1}. The float's heading is recorded once a second with a resolution of 1 ^{o}. The float took six seconds (or less) to respond to this change in vertical velocity. The drive motor responsible for raising and lowering the float takes several seconds to change directions.*

for eight $6'' \times 6''$ paddles oriented at 30^o to the horizontal on $8''$ arms), 0.3 deg s^{-1} would correspond to a vertical velocity of about 9.3×10^{-4} m s^{-1}. This velocity is comparable to our lowest vertical velocities. It is possible that there was a mean vertical velocity in the tank due to differentail heating — one side of the tank was exposed to direct sunlight. Since this "mean" vertical velocity is on the same order of our slowest vertical velocities, it was necessary to remove this mean rotation before calculating ω. The uncertainty in ω is larger at the slower vertical velocities.

Conclusions

Over the range of vertical velocities at which the float was raised and lowered, the rotation rate of the float varied linearly with the vertical velocity. Although the vertical (diapycnal) velocities that the float may encounter in the ocean will be smaller, we expect this linear relationship to hold for those velocities. The torque in the monofilament line and the ambient circulation in the tank prevented us from verifying this relationship at lower values of w.

The sensitivity of the float to vertical velocity increases with decreasing arm lengths and decreasing orientations of the vanes to the horizontal. The sensitivity does not depend on number or size of vanes. The float with vanes may be compared to a screw with helical threads. For the same vertical displacement the screw would rotate more if the thread angle is decreased, or if its diameter is decreased. Changing the number of vanes is equivalent to changing the fraction of the circumference of the screw covered by threads; changing the size of the vanes is equivalent to changing the area of the thread that makes contact with the nut. Neither of these affect the amount of rotation for a given vertical displacement.

References

Rossby, T., J. Fontaine and E.C.Carter, Jr. 1994: The *f/h* float — measuring stretching vorticity directly, *Deep Sea Res.*, **41**, 975–992.

Voorhis, A. D. 1968: Measurements of vertical motion and the partition of energy in the New England slope water, *Deep Sea Res.*, **15**, 599–608.

Webb, D.C and L.V. Worthington. 1968: Measurements of vertical water movement in the Cayman Basin, *Deep Sea Res.*, **15**, 609–612.

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The Coastal Ocean Lagrangian (COOL) float is an isopycnal f/h float equipped with vanes to measure vertical velocity. Although isobaric vertical current meters have been previously developed and deployed, not much is known about how vane geometry affects the float's response to vertical velocities. We determined the sensitivity of the float's rotation rate to vertical velocity past it for different vane geometries. The float's response to size, number and area of vanes, and the distance the vanes were located from the body of the float were examined. While the float's sensitivity increases with decreasing distance of the vanes from the body of the float and decreasing angle of the vanes to the horizontal, the float's response does not depend on the number or size of the vanes.

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